

Original Paper

Ion-Beam Engineering and Its Application to Micro Machine Processing

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This summary introduces new technology of mechanical engineering using ion beam technique. Ion-beam process is induced from plasma state. Engineering working may not proceed satisfied in equilibrium state but in non-equilibrium as the technology becomes precise and high level. Vacuum deposition, ion plating, sputtering and ion implantation are classified with their energy. Preliminary application of ion implantation to micro-machine processing is reviewed. Aluminum plate was masked, irradiated by nitrogen ion (with 40keV, $10 \mu\text{A}/\text{cm}^2$ and $0.1 \text{ C}/\text{cm}^2$), etched with 0.1 N NaOH. Trench structure of $15 \mu\text{m}$ in depth and a high aspect ratio of 0.9 was achieved.

Key words: ion beam, ion implantation, micro-machine, non-equilibrium, aluminum, nitrogen, trench structure

New materials, especially metals, were developed widely as alchemy and later as metallurgy in human history. In the alchemy age, research was carried out empirically, however, in the metallurgy age it did systematically. In these processes human being obtained new materials by mixing and melting minerals in a furnace. High temperature condition was obtained by fire in the ancient age. After humankind can control fire, they got bronze and ceramic brick. Using bellows to send air by compulsion, they can melt copper with charcoal. Focalizing heat radiation by reflecting furnace enabled them to melt iron, which was a starting stage of modern industry. After the success of the new furnace induces higher temperature, they can develop new materials and produce materials practically.

A reaction inside a furnace is equilibrium chemically. Human being controlled this chemical reaction and constructed phase diagrams of elements.

Recently, the age of non-equilibrium has come. Although Non-equilibrium materials, such as amorphous, alloy semiconductor, duralumin and composite are usually unstable thermodynamically under earth environment, they are usable as long as they stand for long use. For example, iron is the great non-equilibrated material on earth. In air, iron is unstable and deteriorated to stain. In order to protect from oxidization, painting keeps non-equilibrated state of iron.

At room temperature, there exist three states of matter, solid, liquid and gas. Atoms of gas phase move

actively more and more as temperature increases, and finally they are not able to keep neutrality of charge. We term this state plasma. In plasma state, atoms are ionized and decomposed to anion and cation in a vacuum like salt in water. First, how can we get so high temperature at which neutral atoms are changed to plasma? The invention of battery was epoch-making in human history. Humankind used only short moment electric power such as static electricity before the invention of Volta's battery gave them stationary and continuous energy. One electron-volt (eV) is defined as increment of energy when an electron is accelerated by the potential of 1 volt. This energy is equal to 1.6×10^{-19} joule. A particle with 1 eV energy corresponds to a particle with about ten thousand degrees Celsius according to energy-temperature relation; $E = k_B T$, where k_B is Boltzmann's constant. Thus, from electric power we can obtain higher temperature than that from a furnace. When we make a short circuit with dry battery, copper wire and air are changed to plasma state. Because electrons draw a picture on a screen of a cathode-ray tube of color television with a few thousand voltage, they are in ten million degrees at surface of the screen. Electric welding makes iron melting with ten to thirty voltage supply. A discharge processing machine is used for precision processing, and a spot-welding machine is used particularly. These are good examples showing that we can obtain high temperature with arc discharge, plasma discharge and electron beam. Secondly, how can we perform processing, welding or surface improvement before the temperature goes down? To prevent from cool down, we employ vacuum condition and control vacuum technique well.

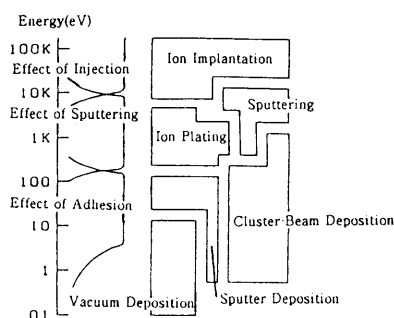


Figure 1. A technique of ion-beam engineering versus beam energy.

Figure 1 shows energy range of beam engineering technique; vacuum deposition, sputtering, ion plating, ion implantation and varied type, molecular beam epitaxy, cluster ion beam sputtering. Kinetic energy of a particle is from 0.1 to 10 eV in vacuum deposition; up to 100 eV in sputtering; 300 eV to 8 keV in ion plating. Methods of new materials development with vacuum technique are as follows.

When material is heated in a vacuum chamber by electron beam or resistance heater, it melts and vaporizes and adheres to a substrate like a mist particle. The technique is called vacuum deposition. Temperature of vaporization is a few thousand degrees Celsius. Because the energy is less than 0.1 eV, adhered force is not strong and it is nearly thermal equilibrium state. In ion plating, vaporized atoms are ionized by discharge or electron beam collision and accelerated to a few hundred electron volt.

Some methods use only discharge energy. Even with a dry battery, it is easy to make ten thousand degrees temperature. When we evacuate air, we can easily get plasma state with rare inert gas. Inert gas such as argon is accelerated by discharge energy. The atoms sputter materials. There are some sputtering methods; direct current (D. C.), radio frequency wave (R. F.) and micro wave. Sputtering method performs a high processing rate. It is applied to composite or dielectric materials and is used in semiconductor processes.

There is the most high-energy method. In sputtering method, gas is changed to plasma, accelerated and hits materials like a bullet. So what happens if materials are plasmalized and used as a bullet? The method is known as ion implantation. It is severest method because an ion is accelerated by electric field and injected to the bulk surface. Injected energy by ion implantation is 10 to 300 keV or more, which is the same range as transmission electron microscope. In the energy range, penetration depth of the ion is up to 1 micrometer. A source of an injected element is gas or vaporizable compound and ionized by discharge. Most of the ionized

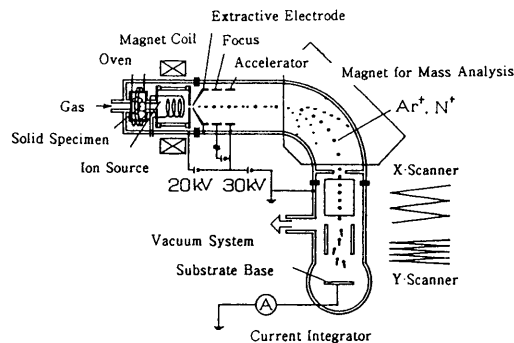


Figure 2. Example of equipment of ion implantation.

atoms are positive ions. They are extracted from plasma gas by negative high voltage, focused by electric or magnetic field like a cathode-ray tube, accelerated by high voltage field again and injected to a target. Figure 2 shows an example of ion-implantation equipment. Source gas is supplied from the left side, or a solid source is vaporized by heater at an oven and transferred by gas. It is ionized by electron beam at an ion source chamber and pulled by electrode, focused, accelerated to 10 or 20 kV. After charged atoms are selected by a mass analysis magnet, they are accelerated totally to 50 keV again, scanned like an electron beam of an oscilloscope by electric fields in horizontal and vertical directions by which ions can irradiate materials with any pattern.

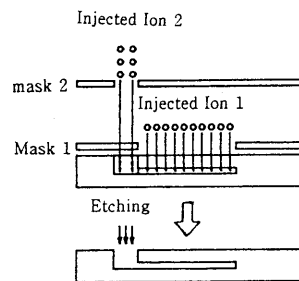


Figure 3. Schematic illustration of micro processing by ion implantation.
(Ion implantation can inject atoms selectively in certain depth.)

We performed a preliminary experiment to make parts for micro-machining. Etching by photo-lithography, which is mainly used in semiconductor processing, is also frequently applied to micro-machine processing. The micro-machining proceeds from the surface. In making of a gear or cantilever, we must prepare a support layer. If ion implantation method is used, ions are injected to the position of 1 micrometer in depth from the surface; we can make process from inside.

A five-nine aluminum plate was covered with aluminum foil as mask from an ion beam, and irradiated by dinitrogen-molecular ion with 30 keV, 10 microampere by square centimeter intensity, 100 millicoulomb by square centimeter (29 mg/cm^2). It is etched for 4 hour in 0.1 normal sodium hydroxide. An etched profile was measured by contact-type surface-roughness meter. Figure 5 shows a cross-sectional profile of the surface. Trenches or deep furrows of about 15 micrometer in depth were made where an aspect ratio was 0.9. It was higher than that of normal etching.

Beam effect is classified as follows.

1) Material injection

- 2) Defect injection
- 3) Sputtering
- 4) Chemical reaction or energy injection



Figure 4. Shape photograph of the ion implanted and etched aluminum.

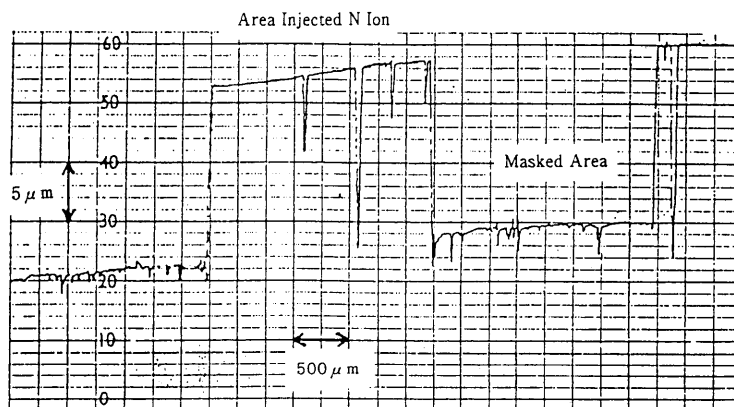


Figure 5. Shape of cross section after etching measured by contact surface-roughness instrument.

Material injection effect clearly appeared in above-mentioned experiment. Nitrogen implanted area was hardly etched in comparison with non-irradiated area. If etching speed differs similarly in the defect injection, it is applicable to processing. The sputtering effect is processing from the surface. Ion milling or surface sputtering is a popular example, but the dose of ions is less than that of normal sputtering. It is disadvantageous for processing. As injection of energy, for example, thin film is fixed to base materials, irradiated, mixed with the base at the interfaced layer and removed. Plasma etching or reactive ion-etching may also be useful.

Recently, Japan Atomic Energy Research Institute Takasaki Radiation Chemistry Research Establishment planned and proceeds a project "Advances Radiation Technology". In this project for radiation research, four ion implantation machines were equipped.

1. High Energy Ion (proton 90 MeV:30 μ A; argon 700 MeV:5 μ A)
2. Middle Energy Heavy Ion (gold 9 MeV:10 μ A; nickel 15 MeV:5 μ A)
3. Middle Energy Light Ion (deuteron 3 MeV:150 μ A; proton 3 MeV:300 μ A)
4. Low Energy Heavy Ion (gold, nickel 400 keV: 30 μ A)

These ion implantation machines will be used for the purpose of drilling small holes by ion beams,

processing a surface precisely, producing new materials (thin films), producing fine particles and controlling structure of a surface. Production of a micro-ion beam with 1 micrometer diameter and 10 picoampere by square micrometer has been planned and tested. A positron-beam factory (source), of which one of author Suzuki is on the committee, is also planned. In the plan, an electron is accelerated to 100 mega-electron-volt and with this energy, matter; a pair with an electron and a positron, is created according to the Einstein's formula $E=mc^2$. This is exact "the creation of matter by energy". We are certainly welcoming the age when we are able to use and control even "anti" matter. Now it is the beginning of new science and technology using ion beams, creating new processing techniques and new materials. Although these researches are big science, we engineering researchers must collaborate on these projects.

New application of ion-beam engineering lead by "light" will become active. Its created materials and processing will be applied to new technology of mechanical engineering.